Miniaturized Balanced Antenna with Integrated Balun for Practical LTE Applications

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Abstract. *A design of dual-band balanced antenna structure operating in the 700 and 2600 MHz LTE bands is studied and investigated. The overall dimensions of the radiator are 50 × 18 × 7 mm^3 allowing it to be easily concealed within mobile handsets. A broad-band balun is designed and integrated with the antenna handset in order to provide the feeding network and perform the measurements of the antenna radiation performance. Prototypes of the proposed antenna with and without balun are fabricated and verified. The simulated and practical results with and without the handheld effects in terms of reflection coefficient, power gain and radiation pattern, are studied and show reasonable agreement.*

Keywords

Balanced antenna, printed dipole, dual-band, LTE, balun

1. Introduction

The demand for researching and developing multi-system handset has increased rapidly in recent years. The design of a wireless transceiver in a smart phone or a portable device must support multi-system operations, since the forthcoming mobile networking ecosystem is expected to constitute legacy and future 5G technology. This raises numerous challenges and requirements for mobile phone antenna designers [1]. To combat these problems, antennas are required to be thin, light, compact design, reduced volume size, and low energy for better incorporating into a portable device. As a result, several works have recently been dedicated to internal multiband antennas in mobile handset applications. The planar Inverted-F antennas (PIFA) [2], [3], microstrip patch antennas [4], [5] and monopole printed structures [6], [7] have been considered as the most common internal mobile phone antennas. In particular, with the advancement of the LTE technology, smart phones are now broadly used, thus designing new antennas for legacy and future release of the LTE standard, catering for carrier aggregation and multiple wideband frequency bands are now of much interest in the research community. Numerous miniaturized LTE handset antennas have been reported [8–13].

By examining the work in [8–13], one can notice that, these antennas have only a single terminal and driven against a local ground plane. Having an antenna along with the system ground plane may help in improving the bandwidth and gain performance. These unbalanced antennas have been exploited in commercial handsets, especially as the mobile device is quite small. However, these unbalanced structures are sensitive to user hand held effect, in that the user´s hand covers a large area of the antenna ground plane in which may change the impedance matching requirements of the antenna and it may lead in performance degradation. This is because the ground plane of such antennas is being used as part of the radiator structure in which a large amount of current would be induced on the radiator as well as on the antenna ground. As a result and while the device is being held by the users' hand, the coupling with the human hand/body, could degrade the antenna performance [14, 15, 16].

To avoid such degradation performance phenomena, a balanced antenna is deemed as a promising candidate for the mobile phone since the current induced on the ground is small or approximately neglected, which leads to minor influences on the performances of the antenna in the scenario of device being held by the user's hand.

To exploit this beneficial property, a number of mobile phone balanced antenna structures operating in dual-band, multiband and wide band have been recently studied [16–27]. Tab. 1 shows the differences between these antennas in terms of operating frequency band, antenna size, power gain and efficiency.

By investigating Tab. 1, one can observe these available balanced antennas can only cover either the major existing mobile bands or/and UWB spectrum, for example: antenna design in [17] can only cover GSM900, the antenna geometry in [18] is capable to work for GSM1800, an antenna operating over the GSM900/1800 was proposed in [19]; whereas [16], [20] proposed antennas to operate in WLAN, authors in [22] proposed balanced antenna structure covering GSM and UMTS, while [23] designed a balanced antenna to operate in GSM and WLAN, and authors in [24] offered balanced antennas that work in the full operation of three mobile radio bands of GSM900/1800, PCS/1900 and UMTS/2200.

On the other hand, several works have been reported to operate over the UWB spectrum, e.g. authors in [25] have proposed an antenna design that operates in both lower bands of UWB from 2.36 to 2.56 GHz and higher bands of UWB spectrum from 5.13 to 12 GHz. Furthermore, in [26], [27] Vivaldi balanced antennas covering the whole range of UWB from 3.1 to 10.6 GHz have been designed and tested.

In contrast, due to the big demand for higher data rate as well as larger bandwidth in recent network of mobile communication, the new technology of the 4th generation namely long-term evolution (LTE) has been developed and newly released. However, none of these balanced antenna designs in [16], [27] have the capability to operate in the range of the lower LTE bands and in particular the lower band of 700 MHz. To address this, we propose a miniaturized printed folded dipole balanced antenna, which operates at dual-band frequency bands of LTE, i.e. 698 to 748 MHz and 2500 to 2690 MHz, for a mobile communication device.

By compromising the bandwidth, antenna size and frequency bands, some approaches were proposed by previous author's works [18], [20–24] to enable wide-band

Ref	Operating Frequency Band (GHz)	Size mm^3 including ground plane	Peak Gain Range (dBi)	Radiation efficiency (%)
16	2.4	118×62.5×0.8	NaN	75.3
17	0.9	100×50×10	NaN	NaN
18	1.8	120×50×12	4	NaN
19	0.9 and 1.8	100×50×6.6	NaN	
20	2.48,5,4 and 6.5	90×40×7	3.5-5.2	NaN
22	0.9, 1.8 and 2.2	120×50×9.5	2.5 -3.5	NaN
23	1.8-2.4	120×50×9.5	2.7-4.2	70-94
25	2.36 - 2.56 and 5.13 - 12	87×35×1	0.7- 5	NaN
26	3.1-10.6	32 × 35 ×1.6	-3-5.25	NaN
27	3.1-10.6	123.5×96.7×1.6	NaN	NaN
proposed	0.7-2.6	100×50×7	0.95-1.7 and 3.8 -4.9	79-95

Tab. 1. Comparison of the performance of the published balanced antennas.

and dual-band functional operation, as shown in Tab. 1. In comparison to [16], [27], this version of the proposed balanced antenna has come up with such advantage of covering the dual-band of LTE namely 700/2600MHz as well as achieving a size reduction compared to previous work in [16–18], [24, 25]. Moreover, this present antenna has achieved a better efficiency in contrast to [16], [23]. Furthermore, it accomplishes an improved gain compared with works in [18, 22, 23, 25, 26].

2. Proposed Antenna Structure

The full configuration of the present dual-band LTE mobile balanced design is shown in Fig. 1. The present design has a simple structure. The antenna is printed over a FR4 material permittivity of 4.4, tangent loss of 0.025 and with a thickness of 1.6 mm. The overall size of the antenna and handheld device is 100 × 50 × 7 mm^3, where the antenna size is 50 × 18 × 1.6 mm^3. A balanced voltage source was used to feed the proposed design. The folded printed arms have a uniform width of 1 mm.

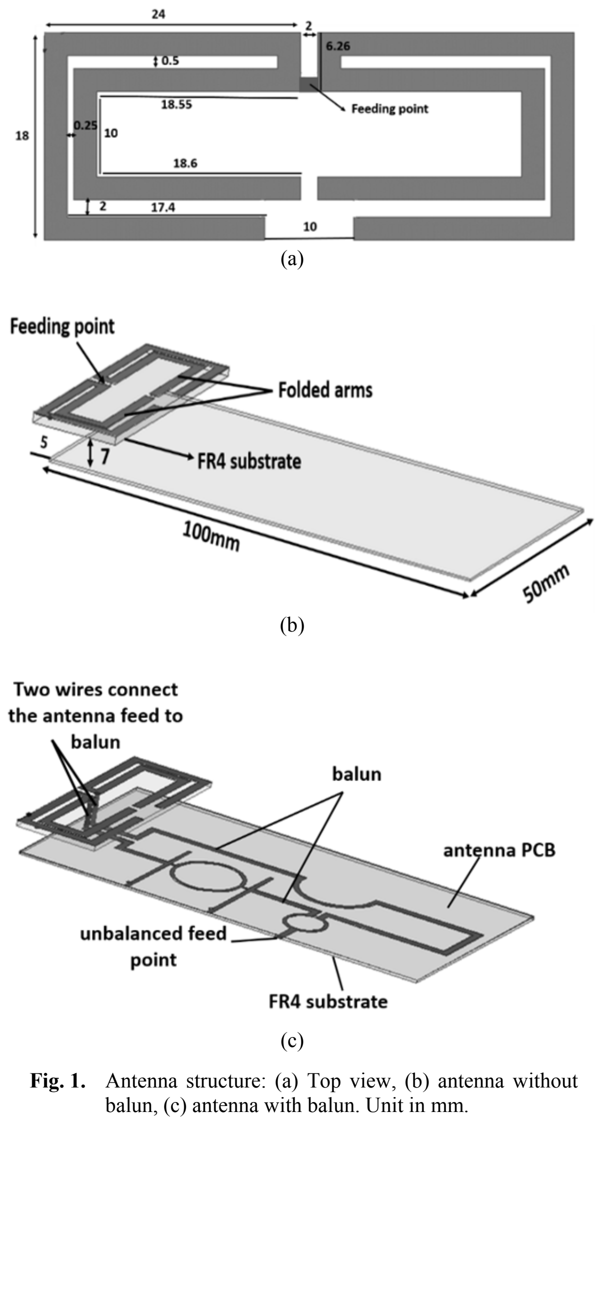


Fig. 1. Antenna structure: (a) Top view, (b) antenna without balun, (c) antenna with balun. Unit in mm.

The ground plane was shifted backward by 5 mm. This has created a defected area under the radiator which has contributed to enhance and improve the bandwidth of the LTE lower frequency of 700 MHz. The proposed antenna comprises of two printed dipoles arms with separation slot of 2 mm width. Each dipole arm is patterned in a way to create two joint U shapes. The formation of such printed dipole shapes has not only contributed towards the antenna miniaturization, but has also effectively achieved the dual-band LTE frequencies defined within this work in particular the lower band of 700 MHz. It should be noted that different set/shapes of folded arms were attempted on the top of the substrate in which it can pave the path towards the targeted dual-band frequencies of 700/2600 MHz.

To further understand the contribution of the printed folded arms technique in size miniaturization, different antenna designs with several printed folded arms shapes were modelled. In this analysis, four standard different printed arms including L-shaped, U-shaped, L-U shaped and 2U shaped were studied. The dimensions of L, U and L-U shapes are depicted in Fig. 2, while the proposed structure of 2U shapes are already shown in Fig. 1. The variation of the printed folded arms against the response of S_{11} was investigated within this study as depicted in Fig. 2. The simulated S_{11} of L-shaped, U-shaped, L-U shaped and 2U shaped arms of the proposed antenna are shown in Fig. 2. As can be seen, by implementing L-shaped radiator on each arm, the proposed antenna can only operate at 4200 MHz, but, when the U-shape was applied, the current path length of the antenna will be changed in which it will force the antenna to operate at 3500 MHz. On the other hand, by joining L and U shapes together on each side of the radiator, the dual-band paradigm started taking a place for which the proposed antenna is being able to cover the dual-band of 1000/3400 MHz. However, by employing 2U shapes configuration on each arm, the present antenna was tuned to meet the targeted dual-band of 700/2600 MHz proposed within this study.

Planar balun in [28] is used and integrated on the handset of the proposed antenna to support the balanced feeding network, as illustrated in Fig. 1c. One can notice that the ground plane of the antenna was placed on one side of the FR4 dielectric with a thickness of 0.8 mm, permittivity of 4.4, and tangent loss of 0.025, while the planar balun was located on the opposite side as depicted in Fig. 1c. The proposed antennas were modeled using HFSS software package [29]. The locations of two balanced ports of the balun were wisely designated to be exactly in direct position underneath the antenna feeding point on the upper sheet of the substrate. Dual thin cables were exploited in order to join the wide band balun to the antenna feeding point via holes. In this manner, the integration of both the antenna and its balanced feeding system were successfully accomplished. The proposed balun operates over a wider frequency range from 700 MHz to 3200 MHz in which the targeted frequency bands of 700 and 2600 MHz proposed in this work can be easily met.

To further investigate the physical behavior of the antenna, the input impedance of the proposed antennas with and without balun in free space and hand held are studied and investigated as shown in Fig. 3. The values of the input impedance of the proposed antenna for the mentioned five cases were summarized in Tab. 2.

As can be observed from Tab. 2, the proposed antenna for both free space and handheld scenarios exhibits a re-

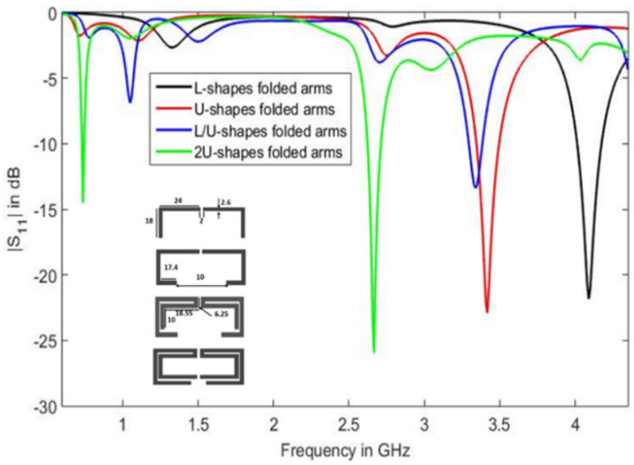
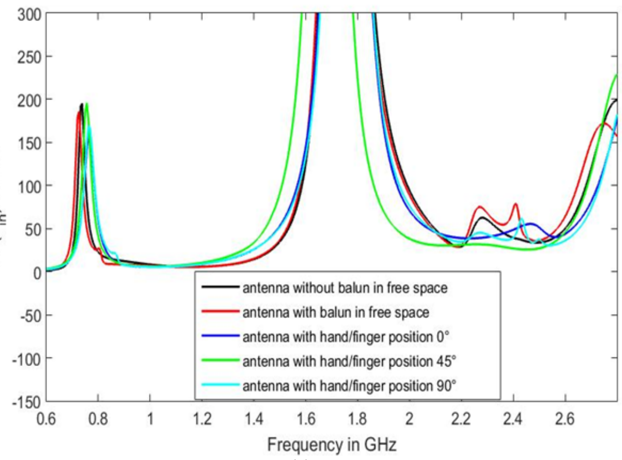
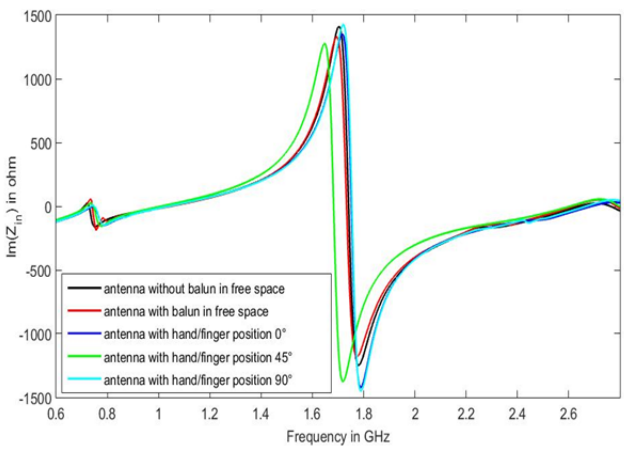


Fig. 2. The variation of the printed folded shapes against the response of S_{11}.



(a)



(b)

Fig. 3. Input impedance of the proposed antenna.

Impedance (Ω)	Antenna without balun in free space	Antenna with balun in free space	Antenna with finger position at 0°	Antenna with finger position at 45°	Antenna with finger position at 90°
Resistance 700 MHz	50	50	46	47	49
Reactance 700 MHz	0	0	–3	–3	–2
Resistance 2600 MHz	46	49	47	46	48
Reactance 2600 MHz	–2	–3	–3	–3	–3

Tab. 2. Input impedance of the proposed antenna in free space and handheld scenarios.

sistance of around 50 Ω (fluctuated between 46 and 50 Ω) at 700 MHz and 2600 MHz. The correspond reactance values of the five cases for the both scenarios at the dual targeted frequencies of 700/2600 MHz were varied between –3 and 0 Ω. In summary, the antenna response for both free space and hand held scenarios has shown a good impedance matching condition to a 50 Ω load.

3. Measurement and Simulation Results

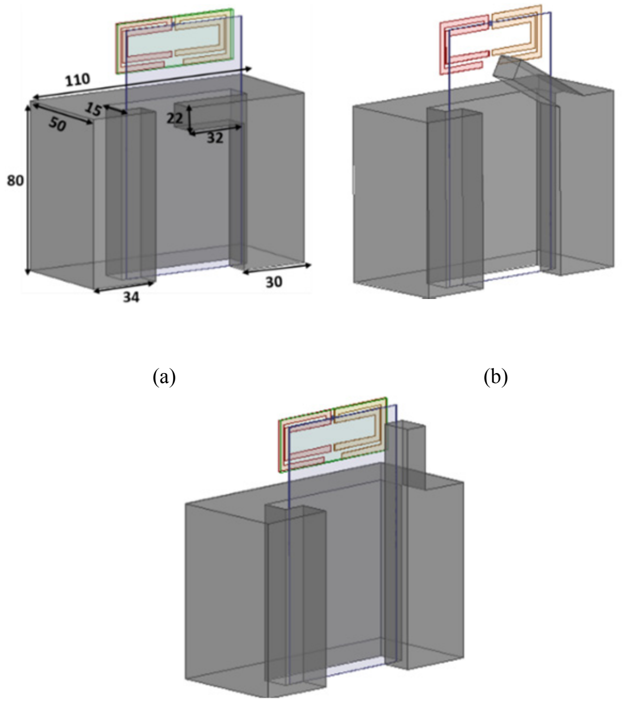
The simulated reflection coefficients of the proposed designs were studied and investigated in the free space and close vicinity to human hand scenarios. The dimension of the hand model surrounding the proposed antenna is assumed as 50 × 80 × 110 mm^3. The antenna and hand model are illustrated in Fig. 4. For simplicity, the proposed hand model is considered to be a muscle tissue of only a single layer, having a relative permittivity material of 54 and a conductivity of 1.45 S·m^{-1} [22], [23].

As depicted in Fig. 4, the hand model takes three typical different configurations of holding the handset, while taking the finger positions into account, i.e., 0° (Left), 45° (middle), and 90° (Right) which are the most common talk positions.

Figure 5 depicts the computed S_{11} for the balanced antenna (i.e., the antenna with/without balun) in free space scenario and including the human hand effect. Observing Fig. 5, it is obviously seen that the $|S_{11}|$ remains below –10 dB over the targeted operational dual-band of 700/2600 MHz in free space scenarios.

On the other hand, in Fig. 5, the S_{11} of the antenna in hand effect paradigm of three positions shows approximately a stable performance in term of S_{11} and in good agreement with the free space scenario. This proves the balanced antenna is ground plane independent and can be a good candidate for practical mobile applications.

For validation purposes of the simulated S_{11} results of the antenna system without balun, a prototype antenna without the inclusion of balun is shown in Fig. 6(a) and (b). It was initially fabricated based upon on the structure and dimensions as clarified in Fig. 1(b), and then tested. Fig. 7



(a) (b)

(c)

Fig. 4. Simulated hand model, with finger positions, 0° (a), 45° (b), and 90° (c).

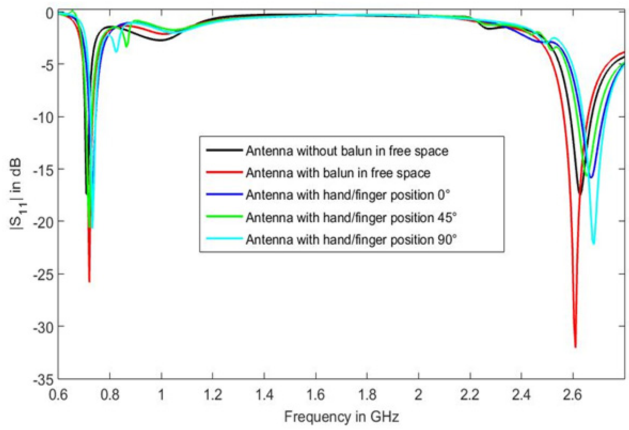


Fig. 5. Simulated reflection coefficients $|S_{11}|$ of the proposed antennas.

shows the measured S_{11} of the present balanced antennas. The S_{11} of the antenna without balun was achieved by utilizing the method of two port network analyzer whereby the integrated balun was not required. Practically, this was accomplished by direct connection of the balanced antenna two ports into the two inputs ports of a calibrated vector network analyzer. One can clearly observe that the measured results of S_{11} are said to be in fair agreement with the computed results shown in Fig. 5, where the targeted LTE dual-band, 700/2600 MHz was accomplished.

For verification purposes, the full antenna prototype assembly (antenna and balun) has been manufactured and measured as depicted in Fig. 6(c), (d). The measured S_{11} of the antenna with the integrated balun is indicated in Fig. 7.

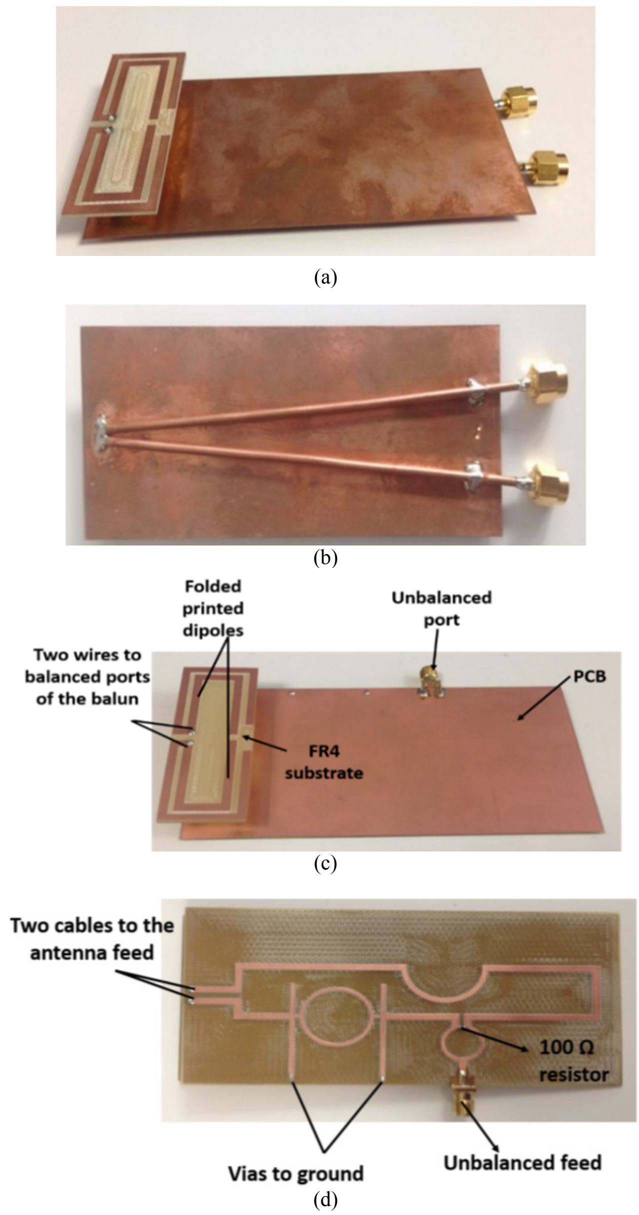


Fig. 6. The antenna prototypes, (a) 3D without balun, (b) bottom without balun, (c) 3D view with balun, (d) bottom view with balun.

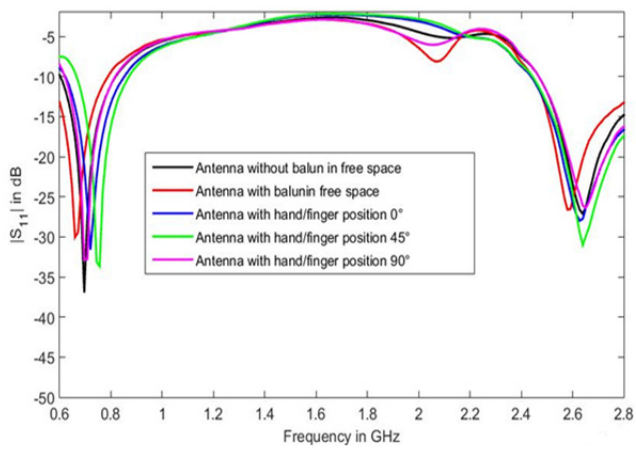


Fig. 7. Measured reflection coefficients $|S_{11}|$ of the proposed antennas.

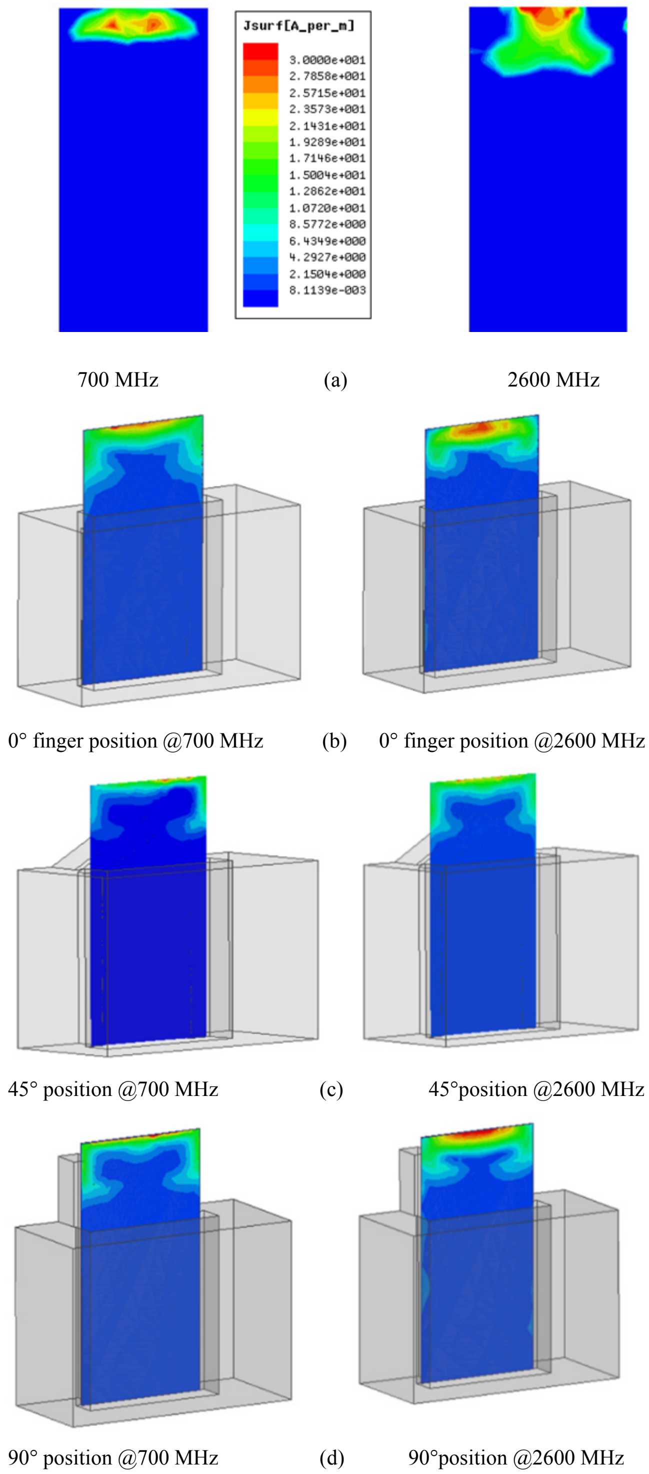


Fig. 8. Current surface for (a) antenna in free space, (b) antenna with hand finger 0° position, (c) antenna with hand finger 45° position, and (d) antenna with hand finger 90° position.

As can be observed, the measured S_{11} of the full antenna assembly shows a good result covering the suggested dual-band frequency spectrum. The results agree well with the computed results as demonstrated in Fig. 5.

The effect of hand holding scenario on the S_{11} performance of the prototype antennas was also studied and investigated in which the ground plane was considered as being held in a hand and positioned in the above-mentioned "talk" positions, shown in Fig. 4. It was noticeable that slight discrepancies occurred between the simulated and measured values of S_{11} in free space within the envisioned operating bands as shown in Fig. 7.

In order to explain how the balanced antenna is ground plane independent, a study of the current intensity of the present design in both free space and hand held scenarios are shown in Fig. 8. The surface current distributions in free space were illustrated over the dual-band of 700/2600 MHz. It is shown that the surface current induced on the antenna ground plane is strong in the area exactly underneath the feeding point for both frequency bands, while it is neglected over the rest of ground plane as indicated in Fig. 8(a), which is comparable to the results obtained from [16]. It also shows some advantages comparable to the induced current on the ground of the unbalanced antenna in [30].

In the hand model scenario for all finger/talk positions, 0°, 45° and 90°, the major current appears around more or less the similar area in the example of free space, in which the current only exists in the area below the antenna and gradually tapers as we head further away over the whole ground plane as shown in Fig. 8(b), (c) and (d). From the above-mentioned scenarios, this antenna proves the fact that the balanced antenna is ground plane independent. This also suggests that the antenna design has an advantage of being insensitive when it is held by the user's hand.

Figure 9(a) illustrates both the computed and measured gain of full assembly antenna for the 700/2600 MHz of LTE frequencies. The computed antenna gain varies from 0.9 dBi and 1.62 dBi over the lower band of 700 MHz and between 3.5 dBi and 4.4 dBi over 2600 MHz band. On the other hand, the measured gain fluctuated between 0.85 dBi and 1.4 dBi over the bandwidth of 700 MHz, and from 3.45 dBi to 4.3 dBi over the band of 2600 MHz as detected in Fig. 9(a). These minor variations may be attributed to the introduction of the physical integration of the balun with ground of the device, and the possible existence of errors of the connector pins antenna fabrication.

Figure 9(b) shows the radiation efficiency of antenna assembly. The Wheeler Cap method was adopted here as an easier and practical method to measure the radiation efficiency [31–33]; that is based on the measured antenna input resistances in free space and in the cap. It is observed that the simulated and measured results are in reasonable agreement and consistent with the variations of the gain results achieved in Fig. 9(a). It can also be observed that the simulated efficiency varies from 76 to 81 % over the lower band of 700 MHz and from 81 to 91 % over the 2600 MHz; on the other hand, the measured efficiency over the 700 MHz band fluctuates from 80 to 83.6 %, while it varies from 85 to 95 % over the higher band of 2600 MHz.

The simulated and measured far-field radiation patterns of the proposed antenna assembly (antenna and balun) were presented in Fig. 10. Two pattern planes cuts at xz and yz were considered at 700/2600 MHz, respectively. From Fig. 10, a reasonable agreement was observed be-

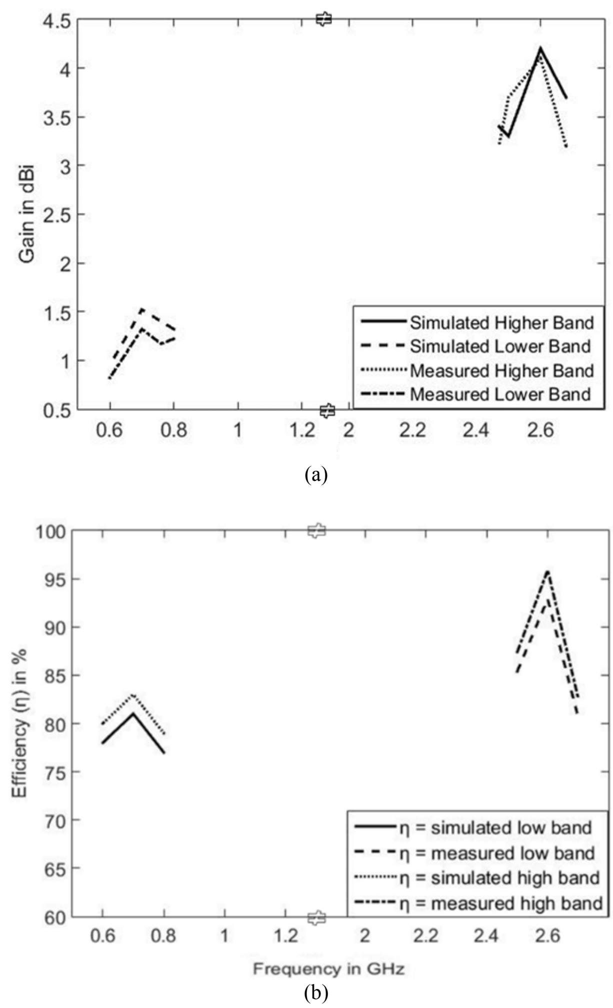


Fig. 9. (a) Simulated and measured gain of the proposed antenna. (b) Simulated and measured radiation efficiency of the proposed antenna.

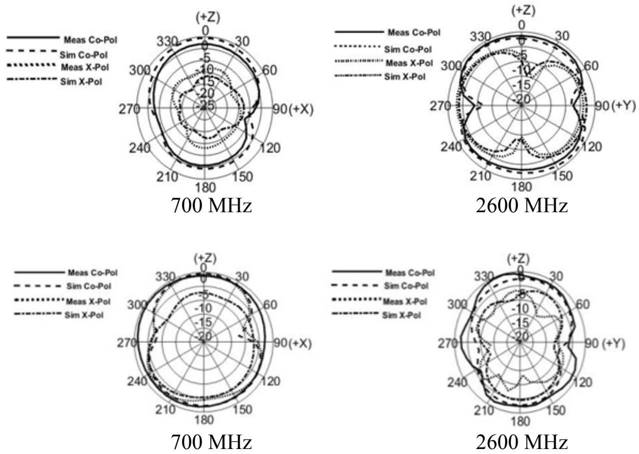


Fig. 10. Normalized antenna radiation patterns for two planes (left: *xz*, right: *yz*) at 700 MHz, 2600 MHz, '____' measured co-polarization, '– – –' simulated co-polarization, '------' measured cross-polarization, '.......' simulated cross-polarization.

tween computed and measured ones. The accomplished results indicate that the radiation patterns are nearly omnidirectional.

4. Conclusion

A balanced antenna covering dual-bands of the LTE standards 698–748 MHz and 2500–2690 MHz has been presented. Computed and measured results of reflection coefficients (S_{11}) showed sufficient impedance matching of $S_{11} \leq -10$ dB including good agreement for free space and hand held with/without balun scenarios. The antenna was demonstrated to exhibit near-omnidirectional radiation over the two operating bands. The surface current of the proposed antenna proves that the currents are diminished over the entire ground plane, except underneath the feeding point where there is improved immunity to the hand-held. This also enhanced the stability of the present mobile antenna to operate at real environment configurations. The antenna could be considered as an attractive candidate for practical applications in mobile phones.

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